KK Parity in Warped Extra Dimension

Work collaborated with K. Agashe, A. Falkowski, and G. Servant: arXiv:0712.2455

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Outline

- Motivation
- A three-site toy model
- The IR-UV-IR setup
- The UV-IR-UV setup
- Conclusion/Discussion/Outlook

Motivation

Many ways to slice the space of BSM theories:

- Supersymmetric:

  MSSM, NMSSM, nMSSM, uMSSM, etc.

- Non-supersymmetric:

  flat extra-dimension (ADD, UED), warped extra-dimension (RS1), little Higgs, Holographic Higgs, Higgsless, etc.

Many ways to slice the space of BSM theories:

- Supersymmetric:

  MSSM, NMSSM, nMSSM, uMSSM, etc.

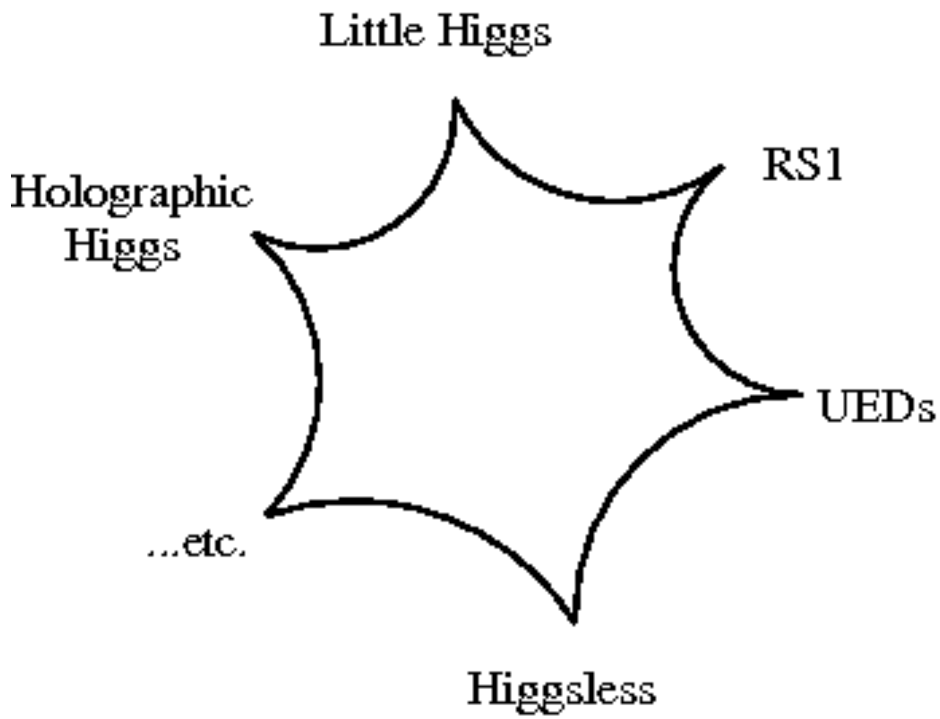
  Essentially they are all cousins of MSSM.

- Non-supersymmetric:

  flat extra-dimension (ADD, UED), warped extra-dimension (RS1), little Higgs, Holographic Higgs, Higgsless, etc.

  It may appear there’s a wide range of variety.

- However it now appears that all the seemingly different non-SUSY theories are also related to one another via “AdS/CFT” and/or “deconstruction”.



Some advocated a “little M theory”?
(Cheng, Thaler, Wang ‘06)

Another way to slice the space of BSM theories:

- A new parity @ TeV scale:

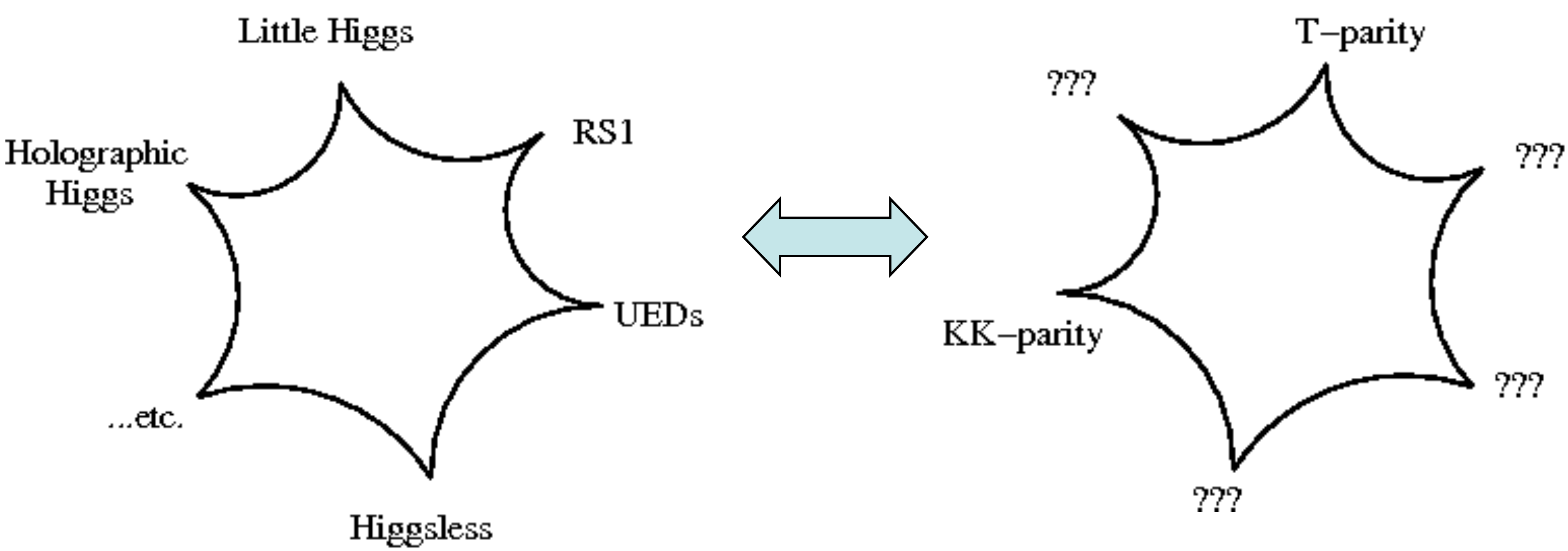
  SUSY (R-parity), flat extra-dimension (KK-parity), little Higgs (T-parity)

- No new parity @ TeV:

  warped extra-dimension (RS1), Holographic Higgs, Higgsless, gauge-Higgs unification.

A Top-Down Viewpoint:

- If we believe there's a continuous spectrum in the space of non-SUSY theories, there ought to be ways to implement the Z_2 parity in models other than little Higgs and UEDs.



A Bottom-Up Viewpoint:

Collider signatures of theories with and without a Z_2 parity are two disconnected sets.

- A new Z_2 parity: Pair-production of parity-odd particles, resulting in missing E_T, multiple jets, and multiple leptons.

  Missing E_T comes from the lightest parity-odd particle if it's neutral. (Also a dark-matter candidate.)

  Events with new particles are always associated with missing E_T.

A Bottom-Up Viewpoint:

Collider signatures of theories with and without a Z_2 parity are two disconnected sets.

- No new Z_2 parity: new particles can be singly produced. Tend to have a smaller number of jet multiplicity. (Can one quantify the statement?)

  Might not have a dark matter candidate which shows up as missing E_T. Even if there's a dark matter, it does not necessarily show up in every event.

  NOT every event with new particles has associated missing E_T.

For example, recently there's a lot of studies on discovering the first KK gluon in RS1 models through its decays to two top quarks:

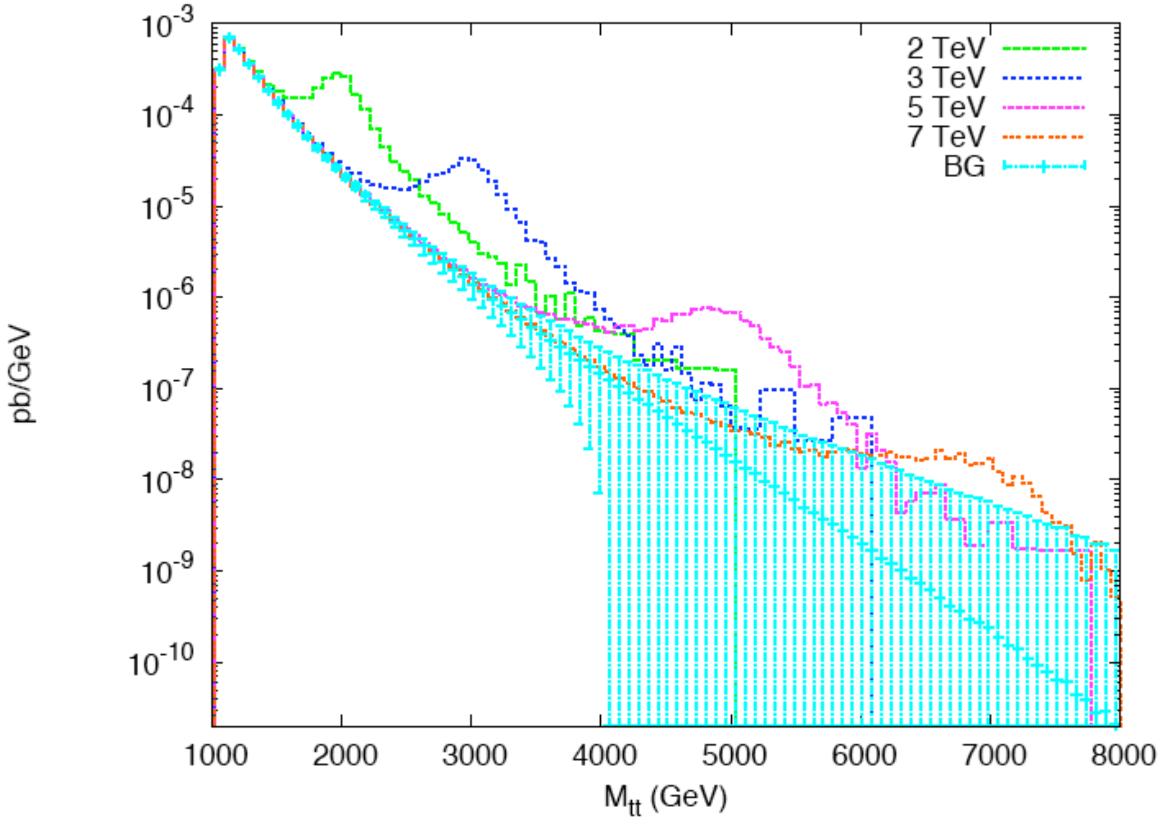
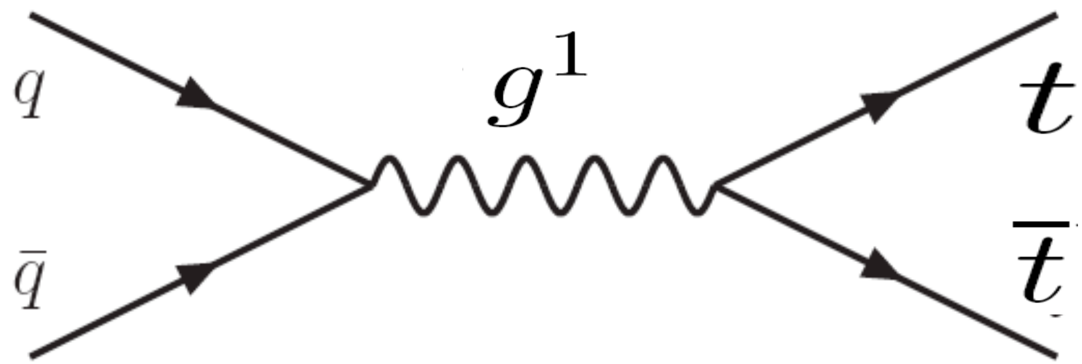


Figure 3: Invariant mass distribution of $t\bar{t}$ pairs coming from the KK gluon resonance, and SM $t\bar{t}$ production. The errors shown on the background curve are the statistical errors assuming 100 fb^{-1} of luminosity.

(Lillie, Randall, Wang '07)

At the LHC the KK gluon can be produced through quark - anti-quark annihilation:

$$pp \longrightarrow g^1 \longrightarrow t\bar{t}$$



The KK gluon can be singly produced. Moreover, if both tops decay hadronically, we would see this as a six-jet event with NO missing E_T.

It is then important to understand whether RS-like models could be implemented with a KK-parity.

If not, and suppose at the LHC we always observe missing E_T in a new physics event, one could immediately disfavor classes of models which cannot accommodate a new Z_2 parity.

Classes of models that currently do not come with a new parity are the warped extra-dimension (RS1), holographic Higgs, Higgsless, Gauge-Higgs unification, etc.

The goal of present work is to see if one could implement KK-parity in warped extra-dimensional setup such as RS-like models.

For now, I will not be concerned with the issue of naturalness, ie whether there exists new particles canceling the quadratic divergences of the Higgs mass.

A Toy Three-Site Model

We would like to have an extra-dimensional setup with a warped factor, in which one could have a KK-parity such that

$$\text{KK Parity} = (-1)^n,\ n = \text{KK number}$$

In this case, the standard model (the zero mode) is KK-even whereas the first KK mode is odd.

Just like in Universal Extra Dimensions!

(Appelquist, Cheng, and Dobrescu, '00)

UED's have been very popular, partly because the mass scale of the new particles are very low, ~ 400 GeV, which would allow easy access at the LHC.

The first KK mode can have such a low mass because of KK-parity : they are KK-odd and need to be pair-produced. Thus the correction to precision electroweak observables are loop-suppressed.

However, there's more to the success of UED's than just KK-parity!

One could ask: if the first KK mode is at 400 GeV, because the geometry is flat the second KK mode will be at 800 GeV, which can be produced singly and couple to the standard model directly.

Why didn’t the precision electroweak constraints force the 2nd KK mode to be at 3 TeV, if it has un-suppressed coupling to the SM?

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Why didn't the precision electroweak constraints force the 2nd KK mode to be at 3 TeV, if it has un-suppressed coupling to the SM?

The answer is such couplings are indeed suppressed, albeit *not* due to KK-parity, but due to the (approximate!) KK-number conservation.

In UED's, the bulk geometry is a finite, flat interval in which the whole SM lives.

Momentum along the extra-dimension is quantized:

$$p_5^{(n)} = \frac{n}{R}$$

Momentum conservation in the extra-dimension implies the KK number is conserved:

$$p_5^{(n)} + p_5^{(m)} = p_5^{(m+n)}$$

KK-number conservation forbids a single coupling of the 2nd KK mode with two zero modes (SM) such as

$$c\, A_\mu^{(0)} A_\nu^{(0)} \partial_\sigma A_\rho^{(2)}, \quad c = 0!$$

Nevertheless, momentum conservation is broken by interactions living on the two boundaries, which are loop-induced. (Cheng, Matchev, and Schmaltz '02)

If that's the only source of brane-localized interactions, KK-number conservation is still approximate:

$$c \approx \frac{1}{16\pi^2}$$

In warped extra-dimension, there’s no (not even approximate!) momentum conservation in the extra-dimension due to the curved background.

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⇨ The even KK mode needs to be heavier than 2-3 TeV to be consistent with pEW measurements.

(Just like in usual RS models the first KK gauge bosons need to be heavier than 2-3 TeV.)

On the other hand, we still would like an odd KK mode at around 1 TeV or below.

In UED's (as is commonly known), a 1st KK mode at 1 TeV and a 2nd KK mode at 3 TeV is not possible --

KK levels are (roughly) evenly spaced due to flat background. (Unless large brane-localized interactions are introduced.)

However, in warped extra dimensions a small hierarchy between the odd and even KK modes is entirely possible.

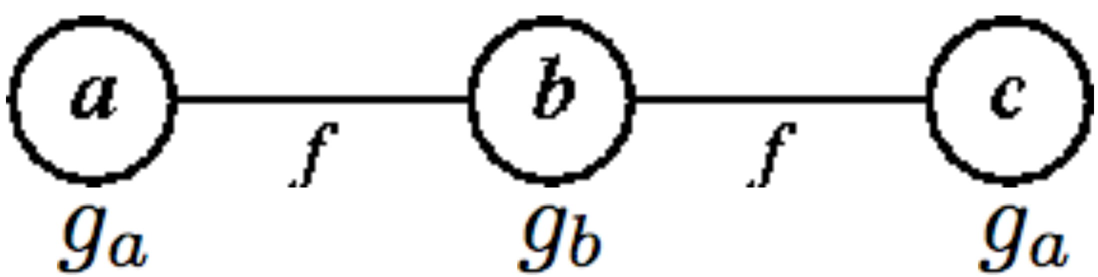
The desired low-energy spectrum:

A modest separation between the odd and even modes such that

$$m_{1_-} \sim 1 \text{ TeV}, \quad m_{1_+} \geq 3 \text{ TeV}$$

In fact, an effective theory below 3-4 TeV, which would describe the zero mode as well as one KK-odd and one KK-even modes, may be all that matter at the LHC.

In other words, we could use a three-site moose model as an effective theory, and impose a reflection symmetry in $a \leftrightarrow c$:

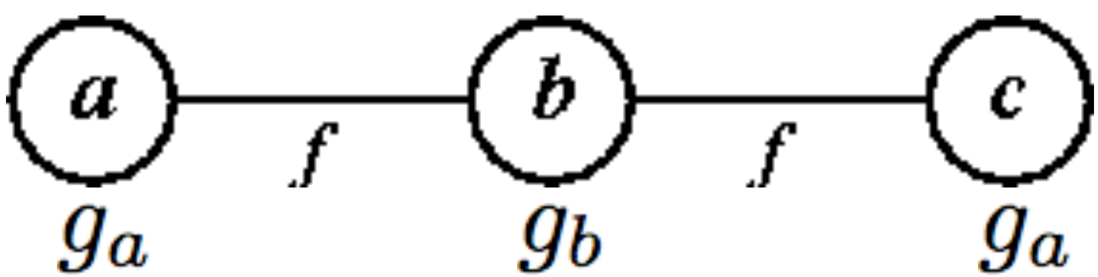


One could work out the mass eigenvalues and eigenmodes:

$$\frac{1}{g_0^2} = \frac{2}{g_a^2} + \frac{1}{g_b^2} \qquad g_0 \text{ is the zero-mode gauge coupling}$$

$$m_0 = 0, \quad m_{1_-} = g_a f, \quad m_{1_+} = \sqrt{g_a^2 + 4g_b^2} f$$

$$\begin{aligned}
A_\mu^{(0)} &= \frac{g_0}{g_a}\left(A_\mu^{(a)} + A_\mu^{(c)}\right) + \frac{g_0}{g_b} A_\mu^{(b)}, \\
A_\mu^{(-)} &= \frac{1}{\sqrt{2}}\left(A_\mu^{(a)} - A_\mu^{(c)}\right), \\
A_\mu^{(+)} &= \frac{g_0}{\sqrt{2} g_b}\left(A_\mu^{(a)} + A_\mu^{(c)}\right) - \frac{\sqrt{2} g_0}{g_a} A_\mu^{(b)}
\end{aligned}$$



There are two interesting limits for the mass eigenvalues:

1) If $g_a >> g_b$, the even and odd modes are almost degenerate.
2) If $g_a << g_b$, the even mode is significantly heavier than the odd mode.

$$m_0 = 0, \quad m_{1_-} = g_a f, \quad m_{1_+} = \sqrt{g_a^2 + 4g_b^2} f$$

$$\frac{g_a}{g_b} \gg 1 \;\; \Rightarrow \;\; \frac{m_{1_+}}{m_{1_-}} \approx 1 - \frac{2g_b^2}{g_a^2}$$

$$\frac{g_a}{g_b} \ll 1 \;\; \Rightarrow \;\; \frac{m_{1_+}}{m_{1_-}} \approx \frac{1}{2}\frac{g_b}{g_a}.$$

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We can think of the three-site model as a "deconstruction" of a warped extra dimension.

A smaller gauge coupling g at a site implies a higher strong-coupling scale locally.

Using the idea of "holographic RG," a site with a smaller gauge coupling would correspond to the UV-region, whereas a larger coupling maps to the IR-region.

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1) If $g_a >> g_b$, the even and odd modes are almost degenerate.

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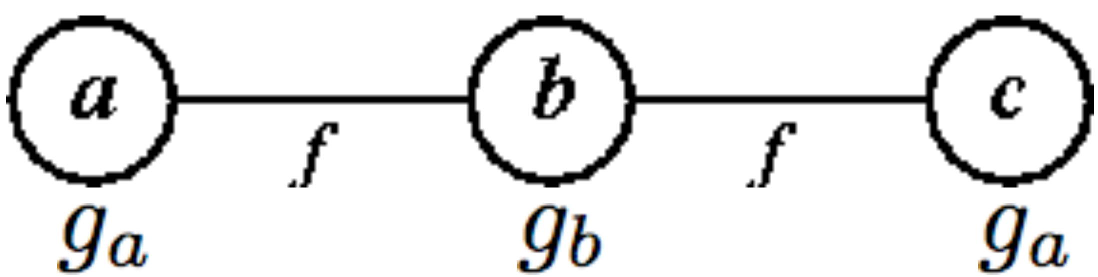
In other words, case 1) corresponds to a IR-UV-IR deconstruction, whereas case 2) is an UV-IR-UV deconstruction.



Furthermore, if one takes the ratio of the gauge couplings to be

$$\frac{g_>^2}{g_<^2} = \log\left(\frac{\Lambda_{UV}}{\Lambda_{IR}}\right)$$

which could again be argued using holographic RG, then the deconstruction even gets the correct "parametric" dependence:

$$\frac{m_{1_+}}{m_{1_-}} \approx 1 - \frac{1}{\log\left(\Lambda_{UV}/\Lambda_{IR}\right)}, \quad \frac{m_{1_+}}{m_{1_-}} \approx \sqrt{\log\left(\frac{\Lambda_{UV}}{\Lambda_{IR}}\right)}$$

To explain the Planck/gauge hierarchy we need

$$\log\left(\frac{\Lambda_{UV}}{\Lambda_{IR}}\right) \approx 30$$

The IR-UV-IR Setup

Let's use the coordinate system:

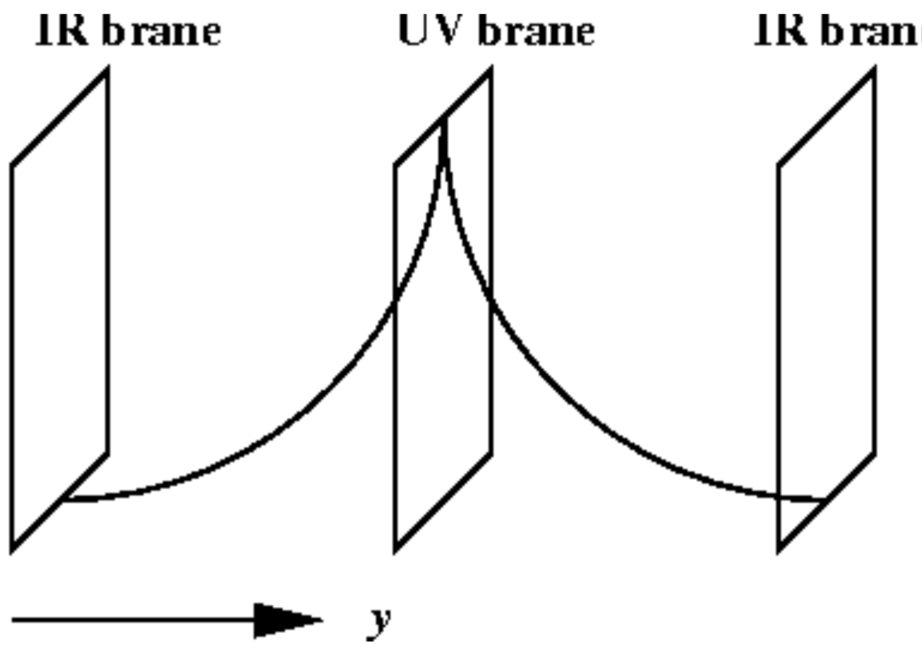
$$ds^2 = a^2(y)(\eta_{\mu\nu}dx^\mu dx^\nu) - dy^2, \quad , -L \leq y \leq L$$

Imposing a Z_2 reflection symmetry in $y \rightarrow -y$ implies

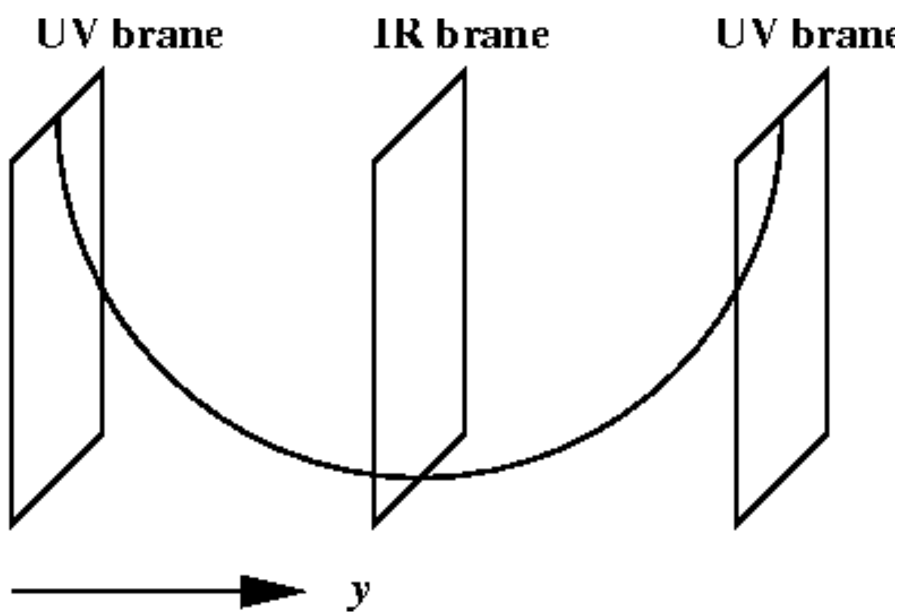
$$a(y) \longrightarrow a(|y|)$$

Moreover, we are looking for AdS-like geometry, in that the warped factor is exponential in *y* near the UV region.

Two obvious possibilities: take the original RS1 geometry and reflect with respect to either the UV brane or the IR brane.



$$a(|y|) = e^{-k|y|}$$



$$a(|y|) = e^{k(|y|-L)}$$

Focus on IR-UV-IR setup for now:

- By continuity of wave functions, KK-odd modes must have Dirichlet B.C. on the “UV” brane, whereas KK-even modes must have Neumann B.C.
- One bulk field is consisted of *two* bulk fields in the usual RS1 models: one has Dirichlet B.C. on the UV whereas the other has Neumann B.C.
- Imposing Neumann B.C. (+) on the two IR branes ensures a massless zero mode for gauge bosons.

In the usual RS jargon, the zero mode and the KK-even tower have (++) ((UV,IR)) B.C., whereas the KK-odd mode has (-+) B.C.

- We confirm the intuition from the three-site toy model that the first KK-odd and KK-even modes are degenerate.
- As explained, this is undesirable from the phenomenological point of view.
- One could understand the degeneracy in the following way:

the difference in the even and odd modes are the B.C.s on the UV brane, but the low-lying massive modes have profiles localized near the IR brane. So the mass eigenvalues should be *insensitive* to this difference.

- In order to break the degeneracy, need to somehow “push” the KK profiles away from the IR brane.

- This is exactly what an IR brane-localized kinetic term (BKT) does -- BKT makes the brane opaque. (Carena, Tait, and Wagner ‘02)

- Thus we expect that IR BKT separates the even and odd modes whereas UV BKT makes them more degenerate.

- In fact, because the profiles are exponentially suppressed near the UV brane, we need very LARGE brane-localized terms on the IR brane.

Define the 5D action as

$$S = -\int dx^4 \int_{-L}^{L} dy \sqrt{-g}\, \frac{1}{4g_5^2}\Big[F^{MN}F_{MN} + 2r_{UV}F^{\mu\nu}F_{\mu\nu}\delta(y) + 2r_{IR}F^{\mu\nu}F_{\mu\nu}\delta(y-L) + 2r_{IR}F^{\mu\nu}F_{\mu\nu}\delta(y+L)\Big]$$

The spectrum for gauge bosons consists of two interlacing towers: the KK-even (++) and KK-odd (-+). There is always a massless mode in the (++) tower.

The two towers are roughly evenly-spaced starting at

$$\sim m_{\mathrm{KK}} = ke^{-kL}$$

- Moreover, each tower has a parametrically lighter massive mode:

For $r_{IR} > L$ or $1/k$

$$\begin{aligned} m_{1_-}^2 &\approx \frac{2}{k r_{IR}} m_{\mathrm{KK}}^2 \\ m_{1_+}^2 &\approx \frac{r_{UV} + r_{IR} + L}{r_{UV} + L} \; m_{1_-}^2 \end{aligned}$$

- For VERY large IR BKT,

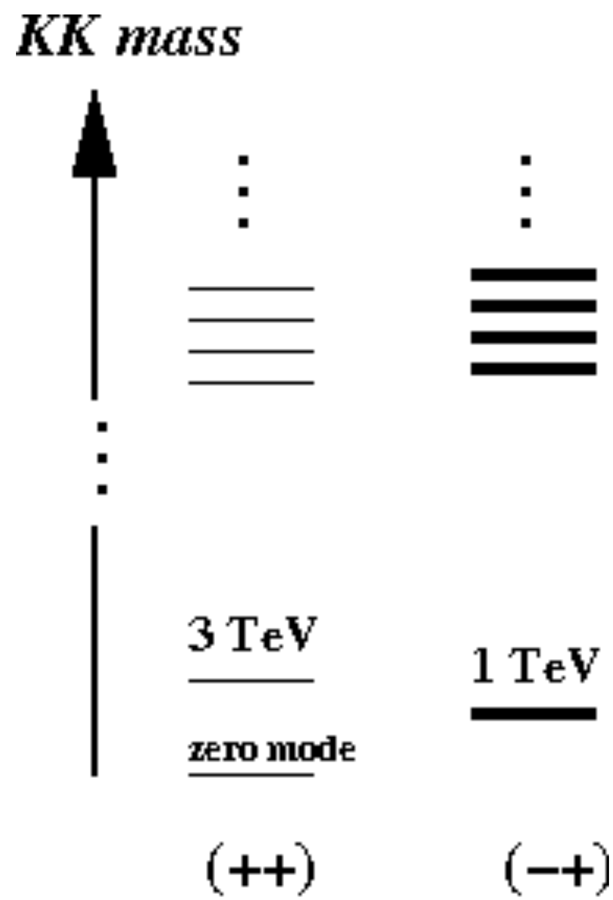
$$k r_{IR} \gg kL : \quad \frac{m_{1_+}}{m_{1_-}} \approx \sqrt{\frac{k r_{IR}}{kL}}$$

- If one requires a modest separation that the even mode is 3 TeV and odd mode 1 TeV:

$$kL \sim 35 \quad \text{and} \quad \frac{m_{1_+}}{m_{1_-}} \approx 3 \quad \rightarrow \quad kr_{IR} \approx 300$$

- Schematically, the KK spectrum looks like

$$\begin{aligned} m_{KK} &= ke^{-kL} \\ &\approx 10 - 20\,\text{TeV} \end{aligned}$$



- The zero mode profile is constant, and the normalization is dominated by the IR BKT:

$$f_0(y) = \frac{g_5}{\sqrt{2r_{IR}}} = g_0$$

- From this relation one might wonder: if we need VERY large IR BKT to achieve a modest separation between even and odd modes, the bulk gauge coupling g_5 would also need to be large. Then we may suffer a loss of 5D perturbativity….

- Indeed, one can estimate the scale of 5D strong-coupling. Let's be conservative and use 4D loop factors

$$\Lambda \sim e^{-kL}\frac{16\pi^2}{g_5^2} \sim \frac{8\pi^2}{kLg_0^2}\, m_{\rm KK}\left(\frac{m_{1-}}{m_{1+}}\right)^2$$

- Using

$$g_0^2 \sim \frac{1}{2},\ \frac{m_{1_+}}{m_{1_-}} \sim 2,\ kL \sim 30 \quad \rightarrow \quad \Lambda \sim m_{KK} \sim 20 - 30\,\mathrm{TeV}$$

- We may have to give up the Plank/gauge hierarchy if we require a perturbative 5D description at the onset of evenly-spaced KK modes.

  A drawback comparing to the original RS1, but certainly an improvement over UED's. Could at least address the flavor scale at ~ 1000 TeV and above.

- We also look at the profiles of the first odd and even modes:

$$f_0(L) \approx f_{1-}(L) \approx g_5/\sqrt{2r_{IR}}$$

$$\frac{f_{1+}(0)}{f_0(0)} \approx \sqrt{\frac{r_{IR}}{r_{UV}+L}} \approx \frac{m_{1_+}}{m_{1_-}} \qquad \frac{f_{1+}(L)}{f_0(L)} \approx \sqrt{\frac{r_{UV}+L}{r_{IR}}} \approx \frac{m_{1_-}}{m_{1_+}}$$

- The even mode coupling to the IR brane is suppressed relative to the zero mode, whereas the coupling to UV brane is *enhanced*.

  (Recall that the IR BKT pushes the profile away from the IR and toward the UV.)

  Important implications to come later…

Now we consider fermions:

- Again one bulk field consists of two bulk fields in the conventional RS1 language, eg the (++) and (-+) modes.
- Suppose we choose the B.C. such that the zero mode is LH. By choosing the bulk mass, the *c* parameter in

$$\mathcal{L}_f = \bar{\psi}\Gamma^M \left(D_M - \epsilon(y) ck\right)\psi$$

the 1st KK-odd mass can be made much lighter than the 1st KK-even mass at m_{KK}

$$\begin{aligned} m_{1-} &\sim m_{\mathrm{KK}} \qquad c > -1/2 \\ m_{1-} &\sim m_{\mathrm{KK}} e^{kL(1/2+c)} \qquad c < -1/2 \end{aligned}$$

- This KK-odd, ultra-light mode can be understood as a would-be zero mode:

  1) the odd mode has (-+) B.C. whereas the zero mode has (++) B.C.

  2) when $c < -1/2$, the zero has a profile “sharply” peaked in the IR.

  3) changing the B.C. in the UV from “+” to “-” therefore produces a very light mode.

From the naturalness point of view, if we were to use this setup to stabilize the Higgs mass, only the KK top quark needs to be light. On the other hand, it is desirable to have top quark localized in the IR.

- For the light fermions, in conventional RS1 they have $c > 1/2$ and are localized near the UV.

  This naturally accommodates the Yukawa hierarchy and flavor symmetry in the RS1, a nice feature.

- In our case, light fermions living near the UV pose troubles -- recall that coupling of the first even mode to the UV brane is enhanced.

  So is the strength of the induced flavor-conserving four-fermi operators

$$\frac{g_5^2}{2L}\frac{1}{m_{1_+}^2} \approx \frac{g_0^2}{m_{1_-}^2}$$

  which constrain the first KK-odd mass to be heavier than a few TeV!

- Therefore, the light fermions cannot be too close to the UV. We find that the constraints can be met for $c \sim 0.5 - 0.55$.

  We will not be able to explain the Yukawa hierarchy through localizations of fermions. It has to be attributed to 5D parameters.

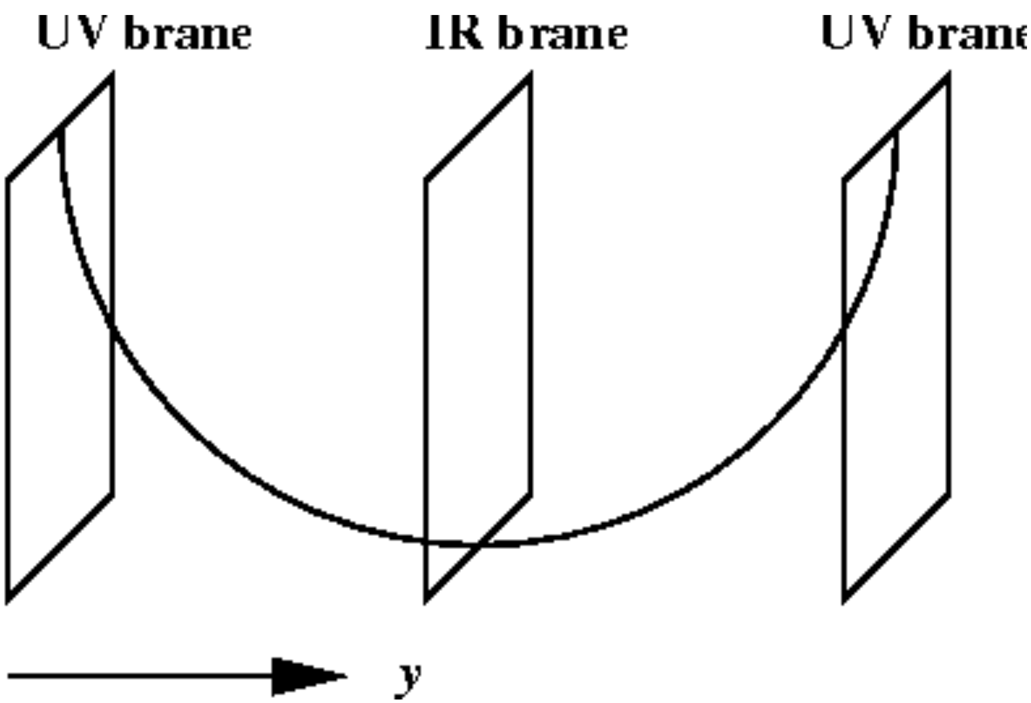
  We may be able to bring the flavor violation in the bulk under control for such a range of c parameters. One could ask what about the brane-localized flavor violation, given that we assume very large IR BKT.

  Obviously this depends on the details of the origin of the brane-localized terms.

  In one sentence, additional mechanism may be necessary to address the flavor problems.

The UV-IR-UV Setup

Now consider two UV branes on the side and one IR brane in the middle:



$$a(|y|) = e^{k(|y|-L)}$$

We again confirm the intuition from the three-site toy model, that there's a natural separation between the even and odd modes in the gauge sector.

- However, the gravity sector of this setup is very troublesome -- the IR brane in the middle has a negative tension -- the radion is a ghost as a result.

  (In the orignal RS1, this ghost is projected out by the orbifold projection.)
- One could try to add a large IR BKT for the graviton. This is reminiscent of the DGP models -- it has been argued that a ghost persists. (Porrati, Luty, and Rattazzi ‘03)
- Another alternative is to consider a continuous warp factor without the negative tension brane such as

$$(ds)^2 = (dy)^2 + \cosh(2ky)/\cosh(2kL)(dx)^2$$

- Such a metric is actually a solution to the 5D Einstein equation with a conformal scalar. In this case the T_{55} component of the stress-energy tensor is negative -- it is the Casmir energy. (Mukohyama ‘00)
- The spectrum is qualitatively the same as the UV-IR-UV setup.
- Nevertheless, the radion in this case is a tachyon. (Hofmann, Kanti, and Pospelov ‘00) It is not clear it can be stabilized.

$$(ds)^2 = (dy)^2 + \cosh(2ky)/\cosh(2k\bar{L})(dx)^2$$

- There is a deeper reason for these troubles -- a *c* -theorem can be proven that, in order to have the UV-IR-UV-like warped factor, weak energy condition must be violated. (Freeman, Gubser, Pilch, Warner ‘99)
- A related pathology has to do with the ultra-light graviton in the setup -- massive gravitons suffer from very low cutoff:

$$\Lambda_3 = (m_g^2 M_{pl})^{1/3}$$

To sum up, even though the gauge sector has a very desirable spectrum phenomenologically, there’s an instability in the gravity sector in the UV-IR-UV setup.

Conclusion/Discussion/Outlook

- Implementing KK-parity in warped extra dimension may bring down the mass scale of new particles, allowing them to be (more) accessible at the LHC.

- Two obvious possibilities are gluing two identical copies of AdS_5, either in the UV region (IR-UV-IR) or the IR region (UV-IR-UV).

- The UV-IR-UV setup suffers from instabilities in the gravity sector. IR-UV-IR setup seems more promising in this perspective.

- In the IR-UV-IR setup one may need to lower the scale of the UV brane to lift the 5D strong coupling scale above m_{KK} ~ tens of TeV.

- Flavor issues also cannot be addressed using the usual fashion. Additional mechanisms are necessary.

- Collider signatures of “warped KK-parity” is the hybrid of UED’s and RS1:

  1st KK modes need to be pair-produced. The LKP could be a dark matter candidate (either *Z’* or RH neutrino). $\Rightarrow$ UED-like!

  KK masses are <u>*not*</u> evenly spaced. $\Rightarrow$ RS1-like!

- It is also interesting to consider the CFT-dual of our setup. It may serve as the guide to implement T-parity in holographic Higgs and gauge-Higgs unification.

- The CFT-dual may also help realize UV-completion of T-parity in the little Higgs, without resorting to supersymmetrized linear sigma model above 10 TeV.

- Much work remains to be done!